Using Neutrons to Diagnose Kinetic Phenomena in Interpenetrating Flows

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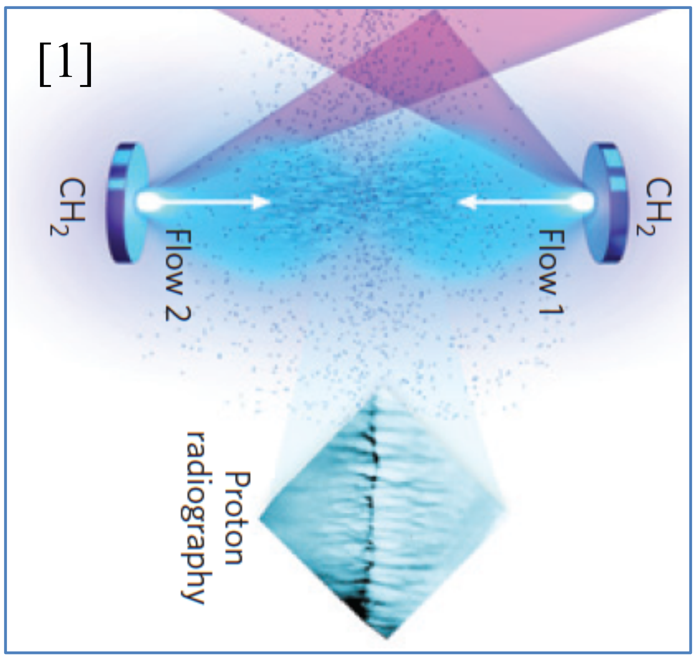
Goal is to Study Astrophysically Relevant Collisionless Shocks

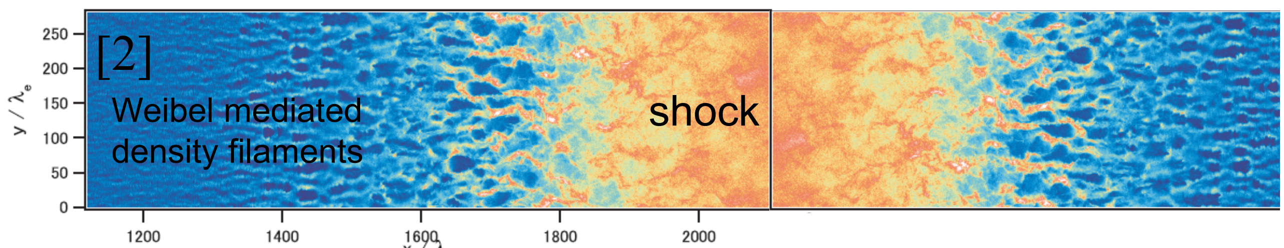
- Collisionless shocks in astrophysical phenomena (e.g. SNR) are thought to accelerate highest energy (10^{19} eV) cosmic rays.

- Experiments at Omega: long Weibel filaments but not enough time/density/space to grow into a shock.



- Experiments at NIF: higher density, larger volume, longer times. Can we drive a collisionless shock at NIF?

- Also, a great platform to investigate kinetic and multi-fluid phenomena.

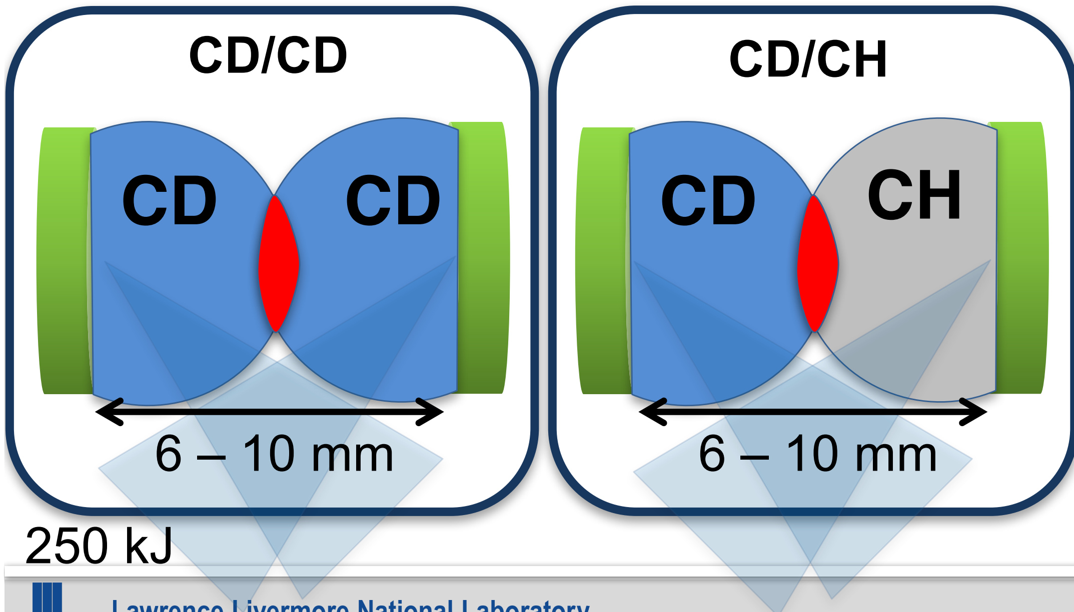


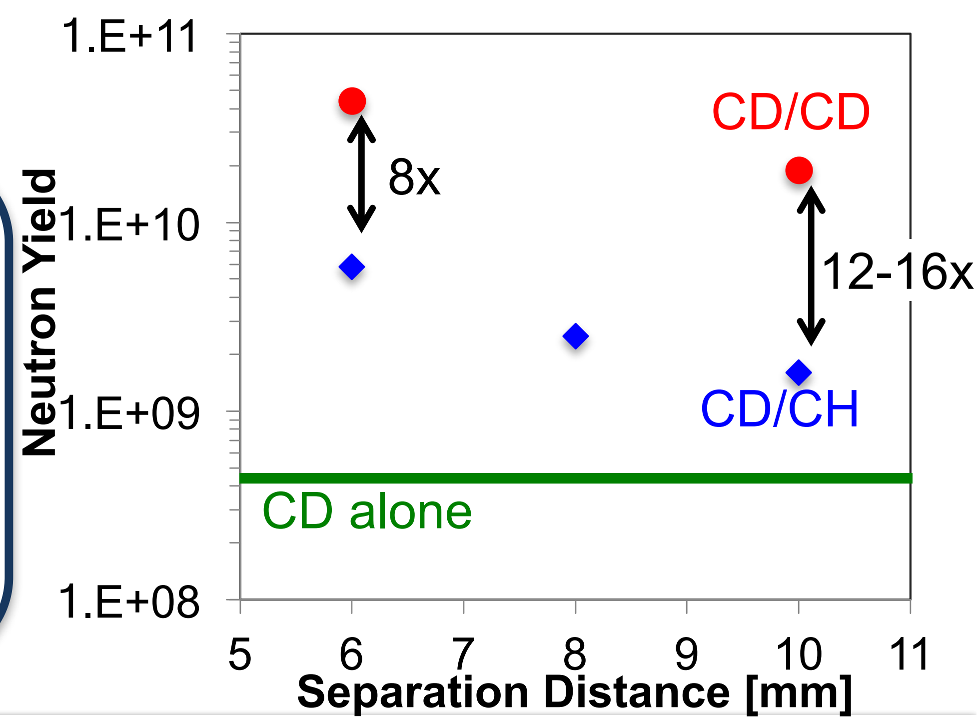
[1] Huntington et al., Nat. Physics, 11, 215 (2015)
[2] Kato et al., ApJ, 681, L93, 2008

Neutron Yield Ratios Suggest a Mildly Collisional Regime

- Yield ratio of CD/**CD**:CD/**CH** on NIF gives insight into collisionality.
- A) Ratio of 2-4x suggests stagnation and shock. B) Ratio of ‘infinity’ (CD/CH = 0) suggests no interaction (i.e. “collision-less”).
- We are in a regime of moderate collisionality between beam. Thus we require collisional, kinetic modeling.

Two types of target (CD/CD & CD/CH)
Different Separations (6 – 10 mm)





Plasma Parameters Suggest Flow is Semi-collisionless Beam-Beam and Collisional Within a Beam

Plasma Flow Parameters

		6 mm	10 mm	
	n_e	3. 10^{20}	6. 10^{19}	cm^{-3} / flow
	$n_{C/D/H}$	4. 10^{19}	9. 10^{18}	cm^{-3} / flow
Beam-Beam	v	1000	1000	km/s
Beam-Beam	$\lambda_{C\text{-}C}$	1.6	3.4	mm
Beam-Beam	$\tau_{C\text{-}C}$	1.6	3.4	ns
Intra-Beam	T_i	1	0.4	keV
Intra-Beam	$v_{th,D}$	220	140	km/s
Intra-Beam	$v_{th,C}$	90	60	km/s
Intra-Beam	τ_{ii}	8	8	ps
Intra-Beam	λ_{ii}	1	0.5	µm

- The mfp for beam-beam collisions is close to the system size. Time scales are similar to the observed neutron duration (1-3 ns).

$$\lambda_{bb} \sim \left(\frac{A}{Z}\right)^2 \frac{\Delta v^4}{Z n_e}$$

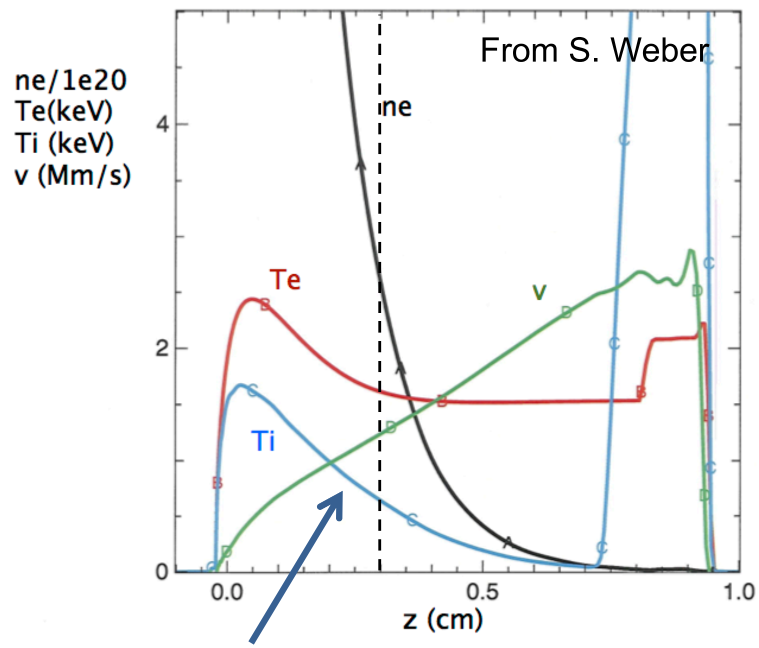
- We can vary the collisionality by changing the separation of the foils to change (n_i).
- Within the beams the ions are collisional with very low mfp.

$$\lambda_{th} = v_{th}\tau_{th}$$

Model Laser with Hydra and Handoff to PIC for Interpenetration

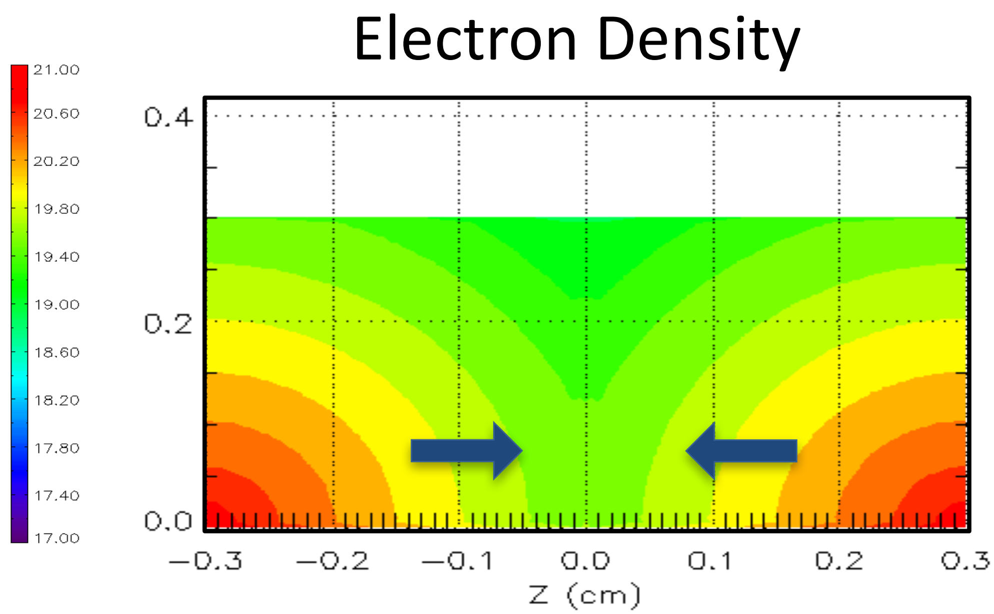
Step 1: Single foil with 2D HYDRA

250 kJ per foil for 5 ns, at 3.5 ns



Take this flow, and send it back against itself. Symmetrize spherically.

Step 2: Opposing foils with LSP

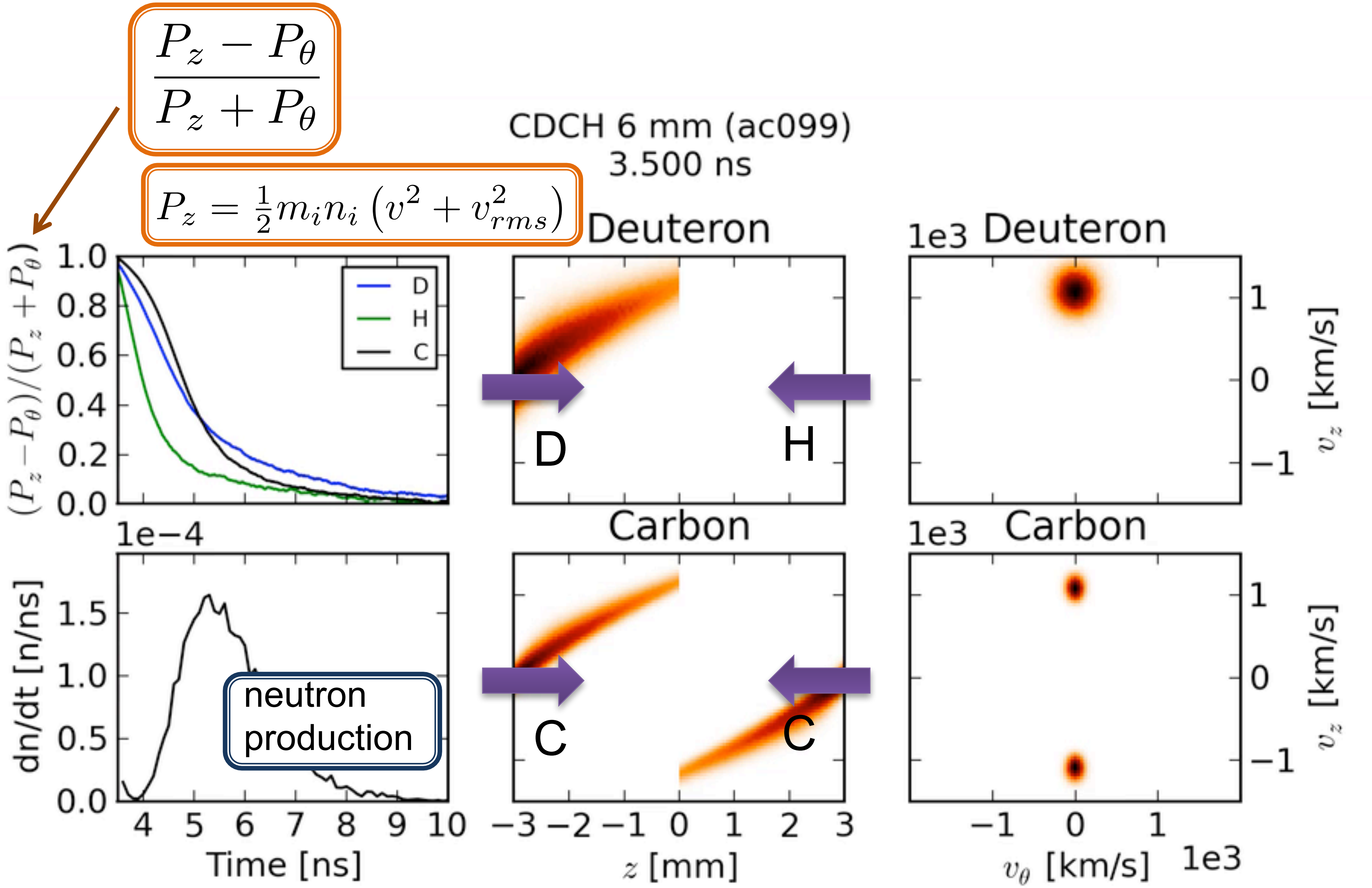


Use LSP (PIC) to model interpenetration and has neutron package.* No EM fields used.

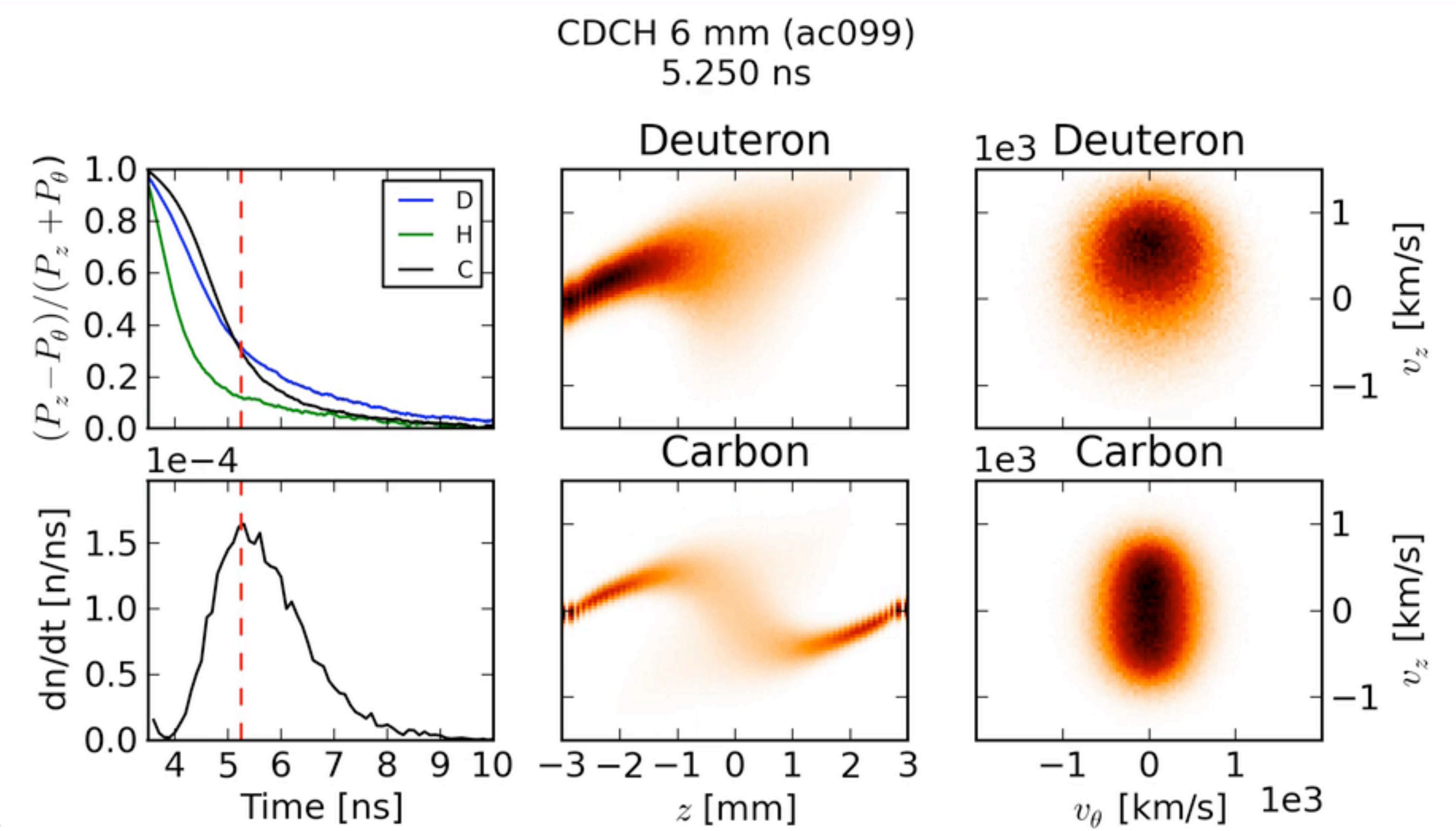
Δx = 20 – 100 μm
Δt = 0.2 ps
1600 part./species/cell

* A. Link

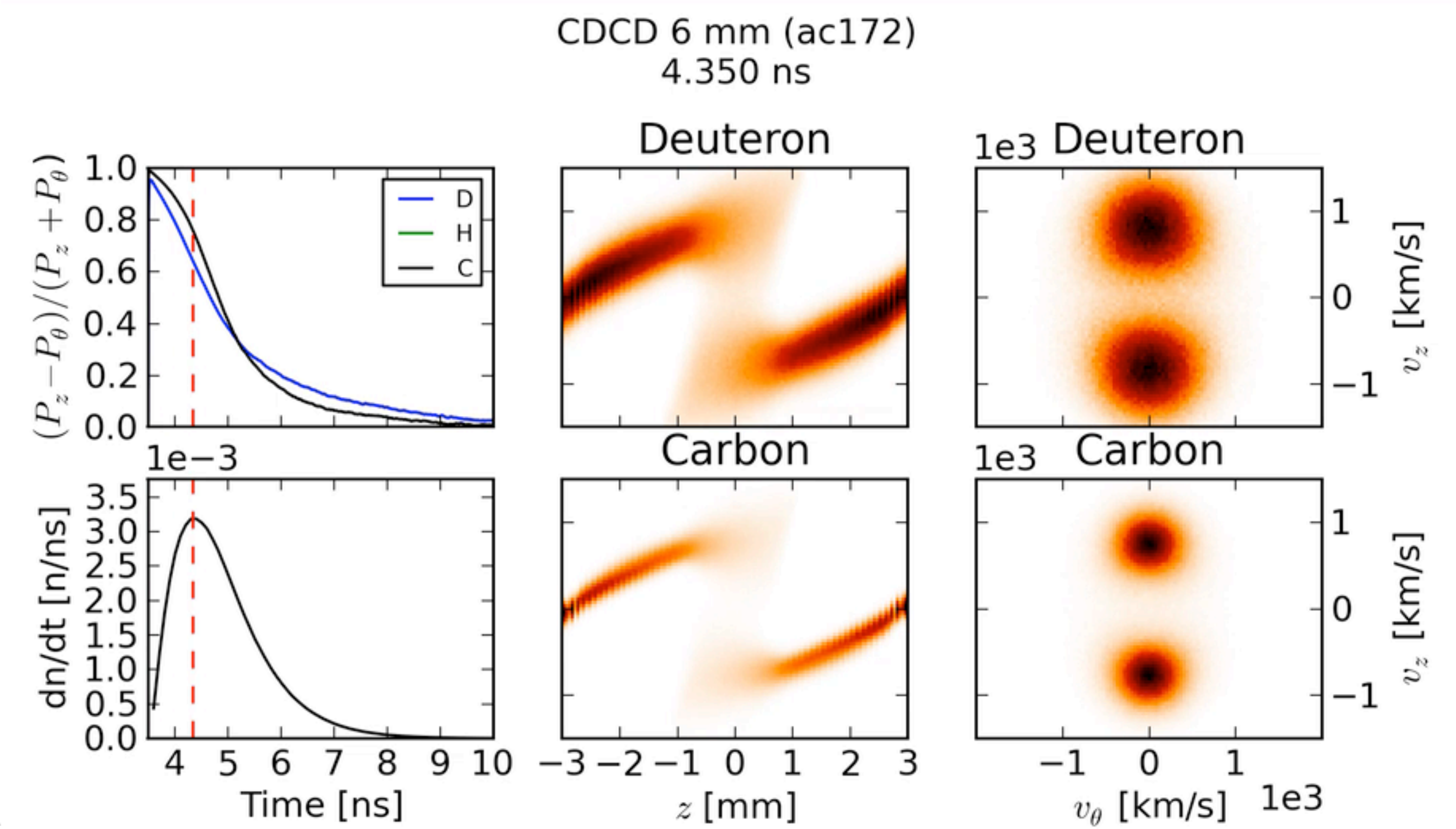
Interpenetration of the flows



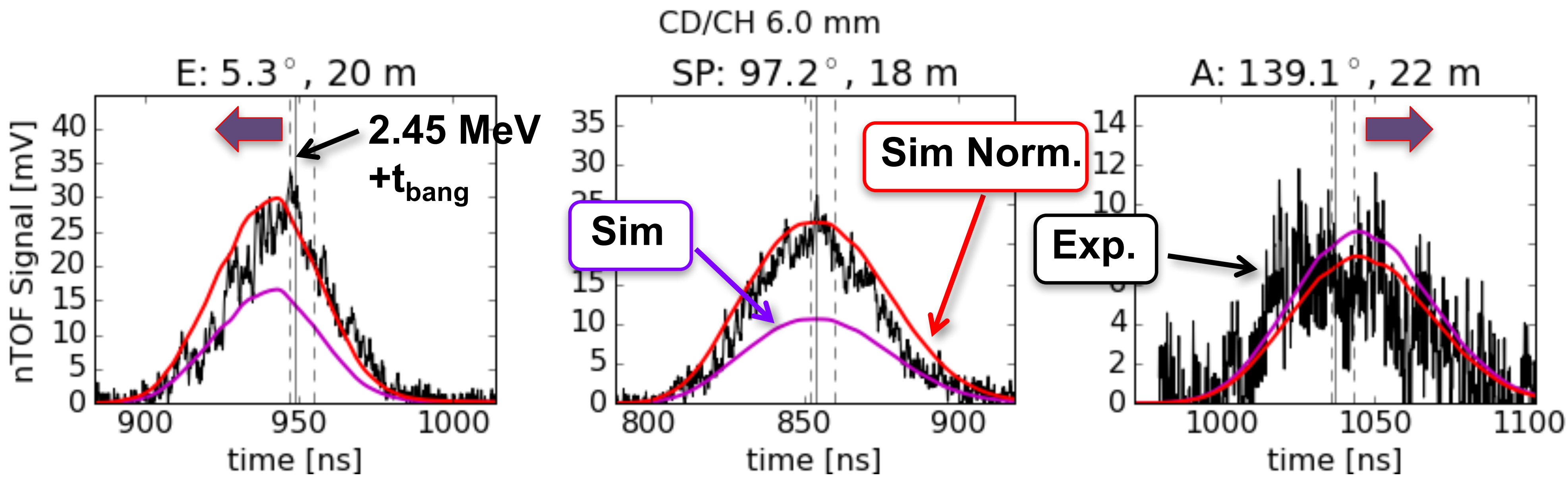
Neutrons Probe Before Thermalization is Completed



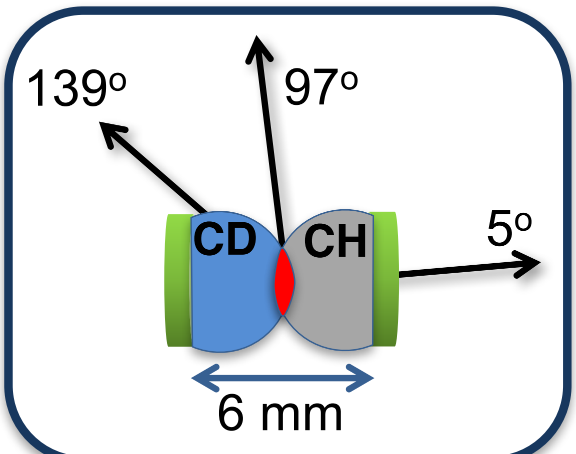
Beam-Beam (CD/CD) Neutrons Probe Even Earlier



Synthetic nTOFs Agree with Data and Show Doppler Shift

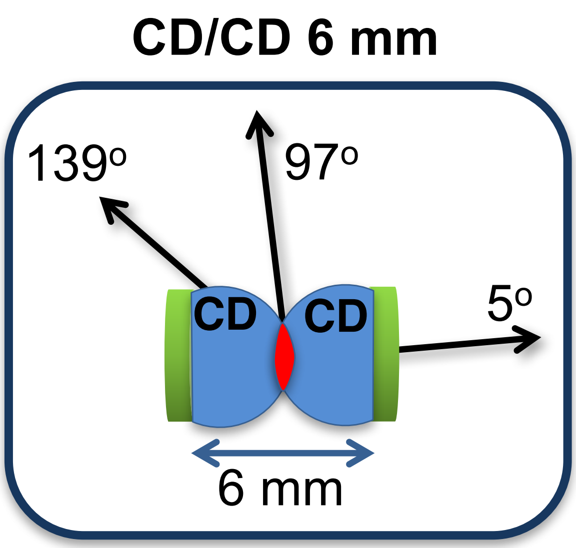


CD/CH 6 mm

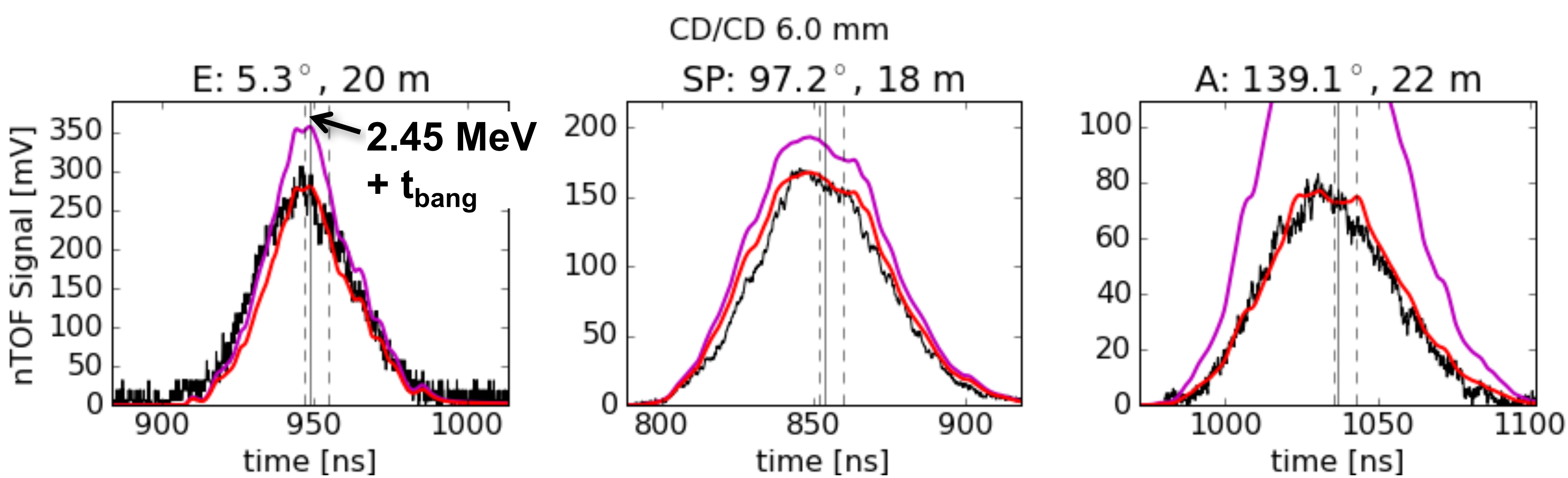


- Simulated Neutrons are run passed through the (time/energy) diagnostic response.
- Reasonable agreement with width and shift. Though not with yield.
- A Doppler is observed in the forward and backward directions.

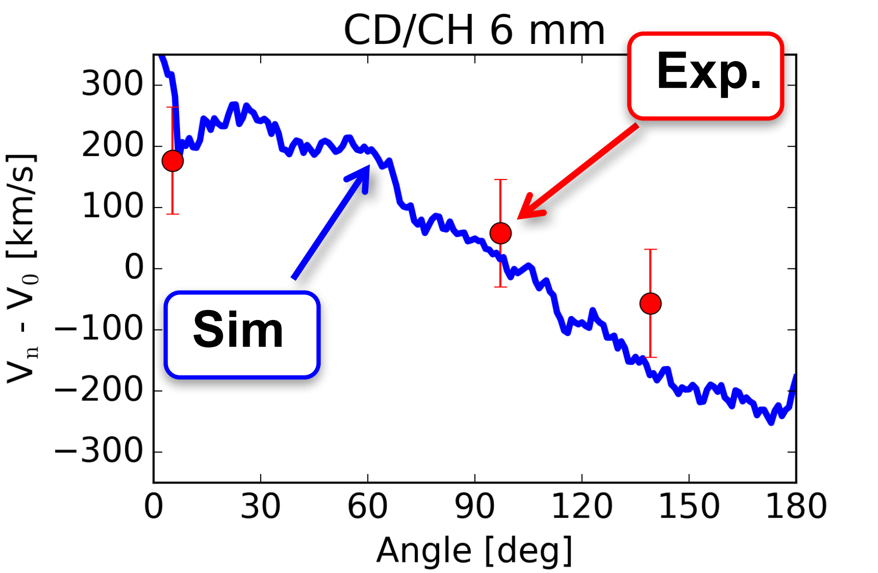
In the Symmetric CD/CD Case Upshift is Observed

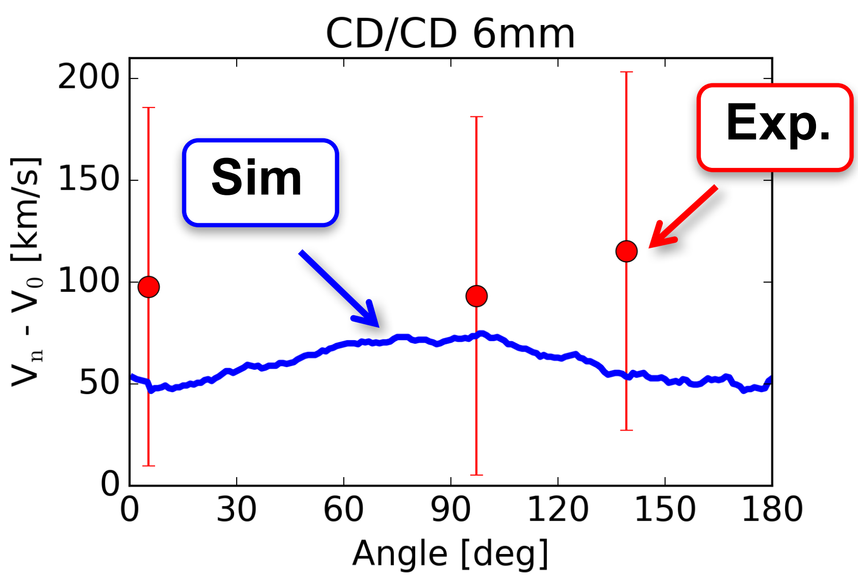


- Again, good agreement with experiment.
- All angles seem to be upshifted in energy.
- The widths of the distributions vary with angle with the largest width at 90°.



Neutron Velocity Shift Mirrors Target Assymetries



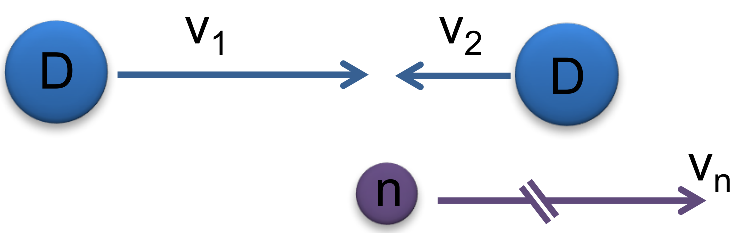


- We observe an angle dependent shift in neutron energy in the asymmetric case.
- We observe a isotropic energy boost in the the symmetric case.
- The data fits come from shifted-Gaussian that is dependent on the bang time*. Error bars may be slightly over conservative.

*from R. Hatarik

Neutron Kinematics

Head-on DD Reaction



$$v_{c.m.} = \frac{1}{2}\left(|v_1| - |v_2|\right)$$

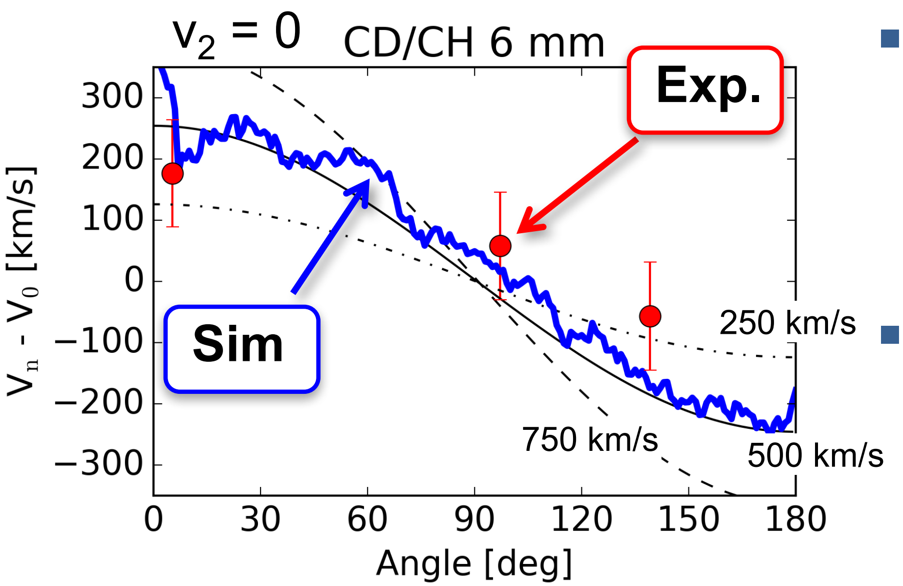
$$v_r = |v_1| + |v_2|$$

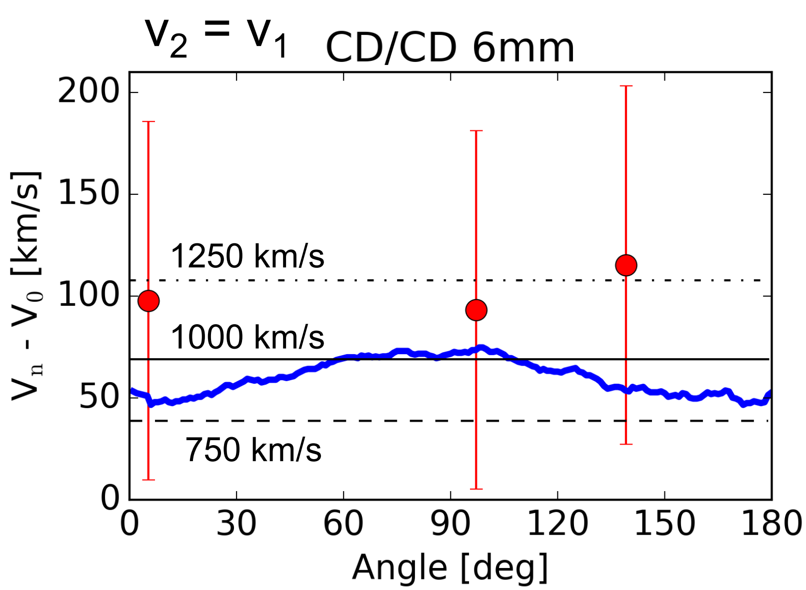
$$v_0 = 21.65 \text{ Mm/s } (2.4495 \text{ MeV})$$

$$\boxed{v_n \simeq v_0 + \frac{0.748}{v_0} v_r^2 + v_{cm} \cos\theta - \frac{1}{v_0} v_{cm}^2 \sin^2\theta}$$

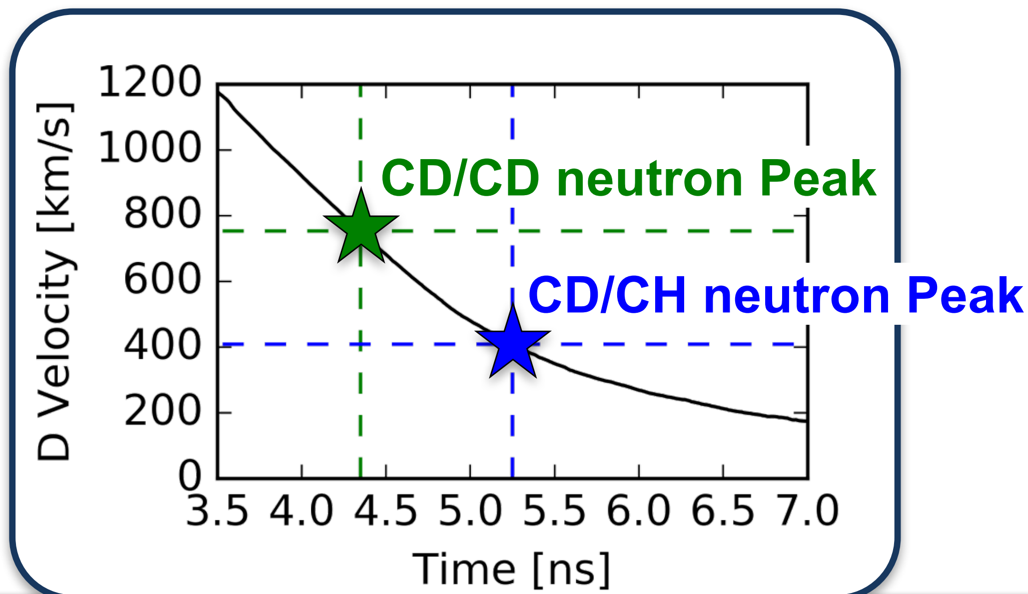
- The neutron energy (i.e. velocity) is dependent on :
  1) The Q-value of the reaction (v_0).
  2) An angularly dependent Doppler shift, which is linearly dependent on center-of-mass velocity.
  3) An isotopic boost of energy from the relative velocity of the interaction.

Deuteron Velocity Recovered from Neutron Energy Shift

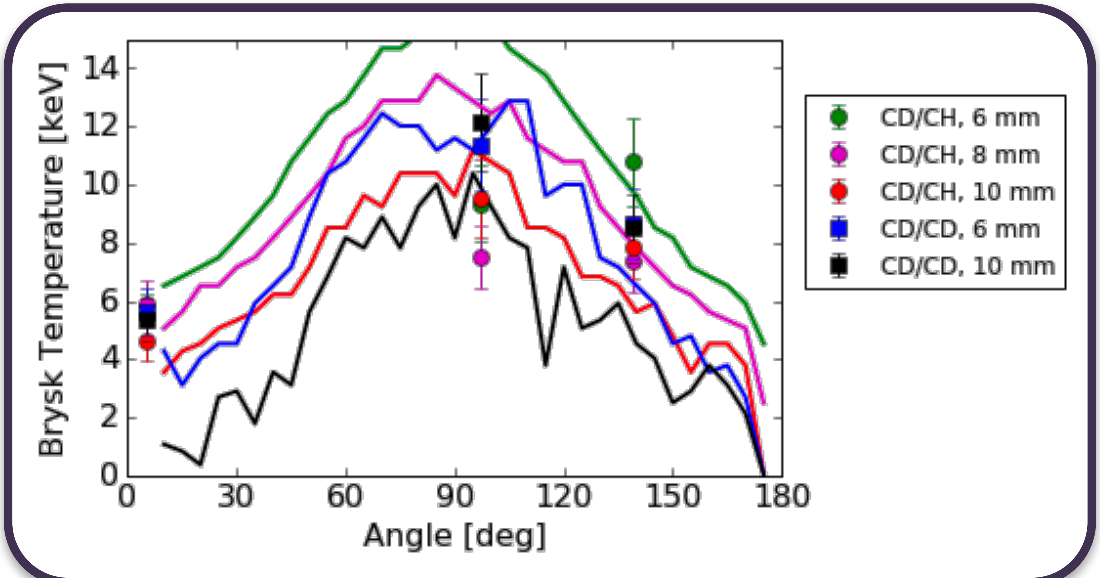


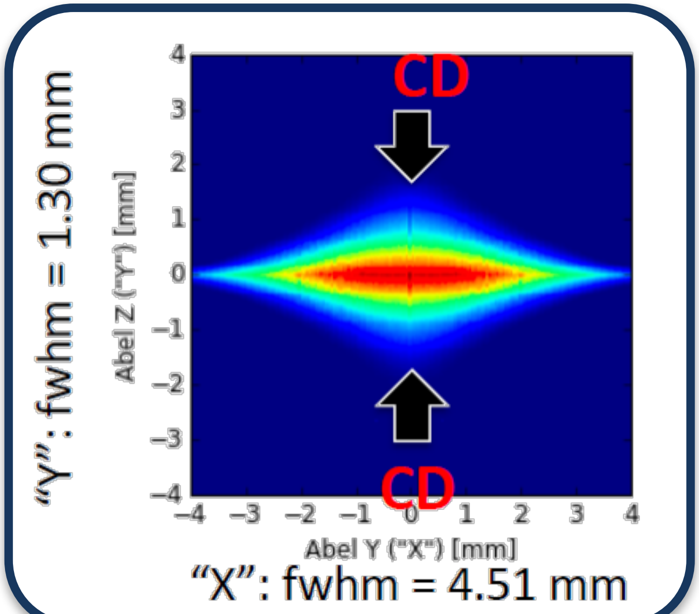


- Fitting the neutron shifts with theoretical values allows flow velocity to be inferred for CD/CH and CD/CD!
- Inferred deuteron velocities are weighted to the neutron emission and thus differ with the target.



The Simulations Seem to Reproduce the Nuclear Data



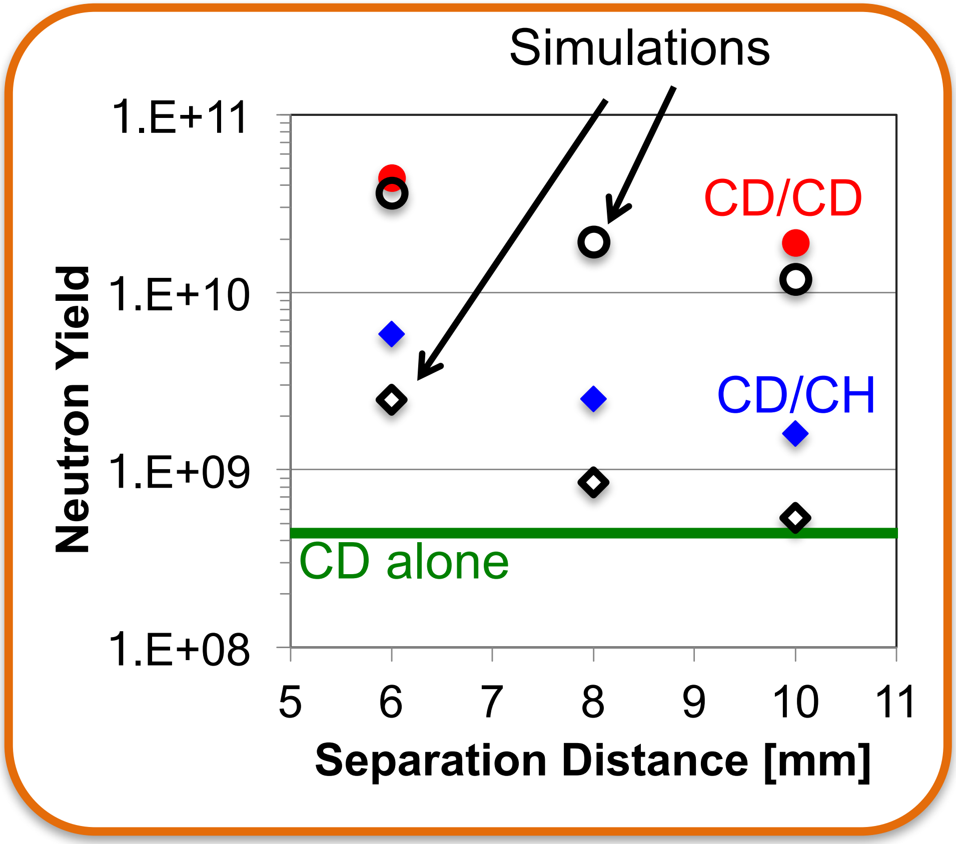


Our simulations agree with :

- Neutron time history (i.e. bang time and burn-width).
- Shape (compared with images of proton self-emission).
- Brysk or "Apparent" ion temperatures. Seems to be a mesurement of radial expansion.
- Velocity shifts

But…

Yet we still find a Neutron Yield Deficiency



- Match to CD/CD yield is fairly good especially at the closest separations.
- CD/CH yield is under-predicted by 3–12 times and gets worse with distance.
- This suggests that we are missing some type of "scattering" as the plasma becomes less collisional.
- This could be due to collision-less (i.e. electro-magnetic) effects becoming important.

Summary

- We have investigated the interpenetration of flows and examined the transition from few collisions into stagnation.
- Neutron diagnostics are found to be an excellent window into the initial stagnation when kinetic effects should be most important. Could be used as a dopant.
- Shifts in the neutron mean-energy are identified as a measurement of the velocity of the flow that is weighted by the production probability.
- There is still something missing in our models that must be included to reproduce the mysteries of our experiments.

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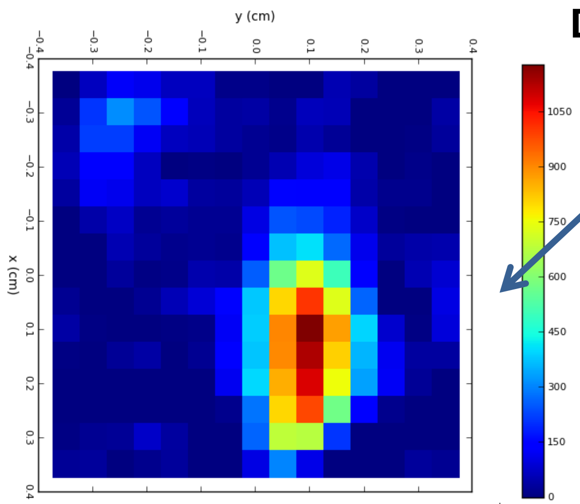
Shape of neutron self-emission is similar to experimental proton images

Spatial extent of the region where fusion is occurring.

Experimental "proton image"

"Y": fwhm = 1.2 mm

"x": fwhm = 3.2 mm



Courtesy A. Zylstra

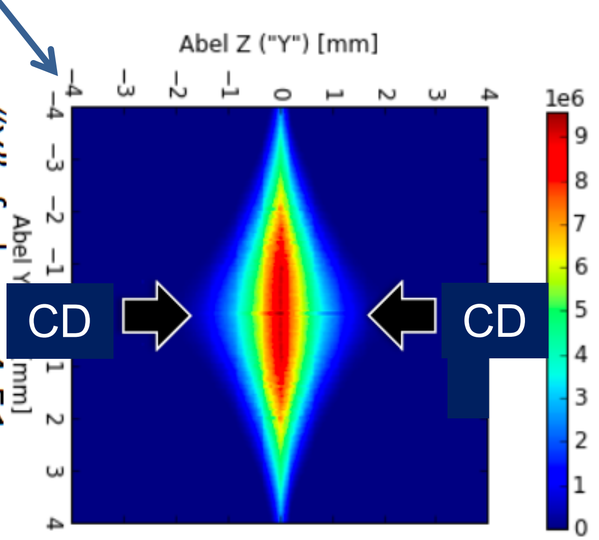
D+D→ ^{3}He + n (2.45 MeV)

D+D→ T + p (3.0 MeV)

Simulated "neutron image"

"Y": fwhm = 1.30 mm

"x": fwhm = 4.51 mm

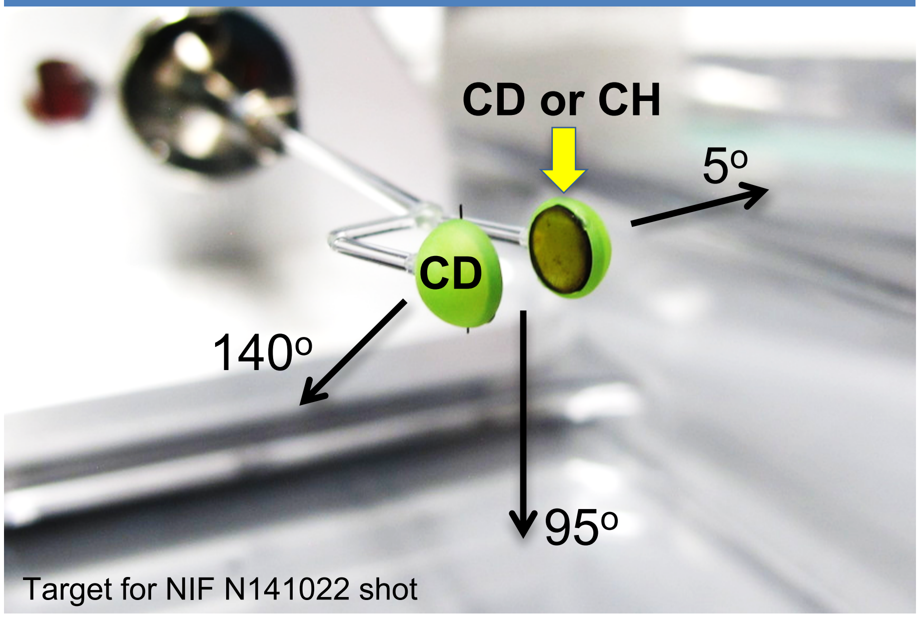


Both images are "pancaked" with similar dimensions
This is further evidence that modeling is doing a decent job of capturing the essential physics.

NIF experiments

Several diagnostics were fielded, but we'll focus on neutron Time-Of-Flight (nTOF)

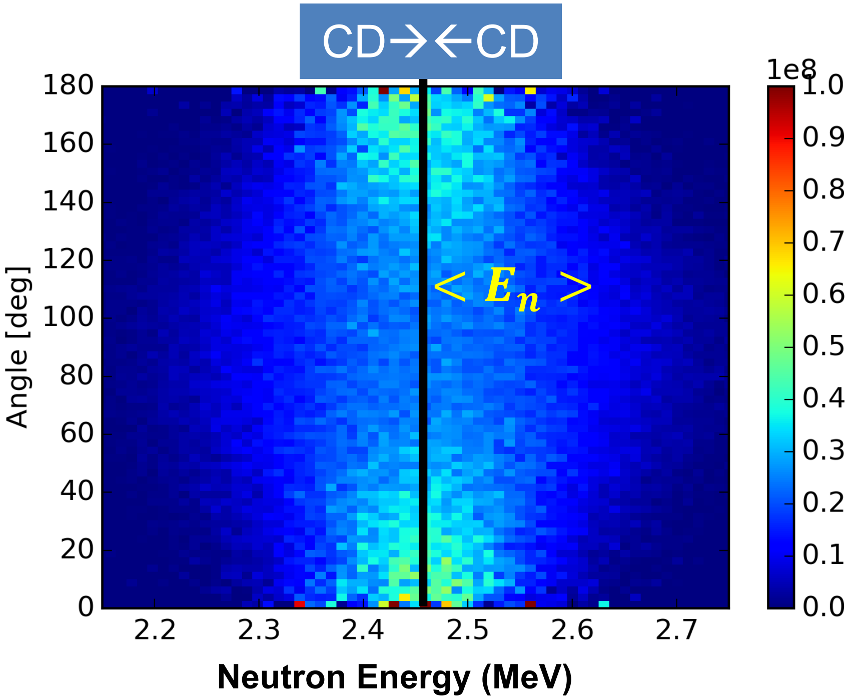
Two different types of target

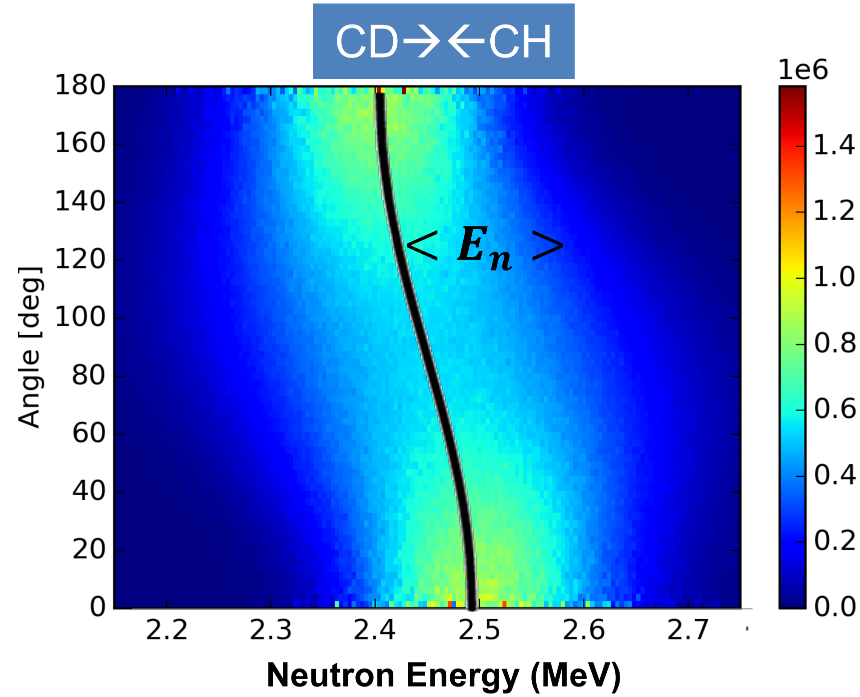


What about the mean energy?

Simulations predicted very different mean energies for the CD →← CH case that should also be present in the experiment.

$$< E_n > = \frac{1}{2} m_n \left(v_n' + v_{flow} cos\theta \right)^2$$





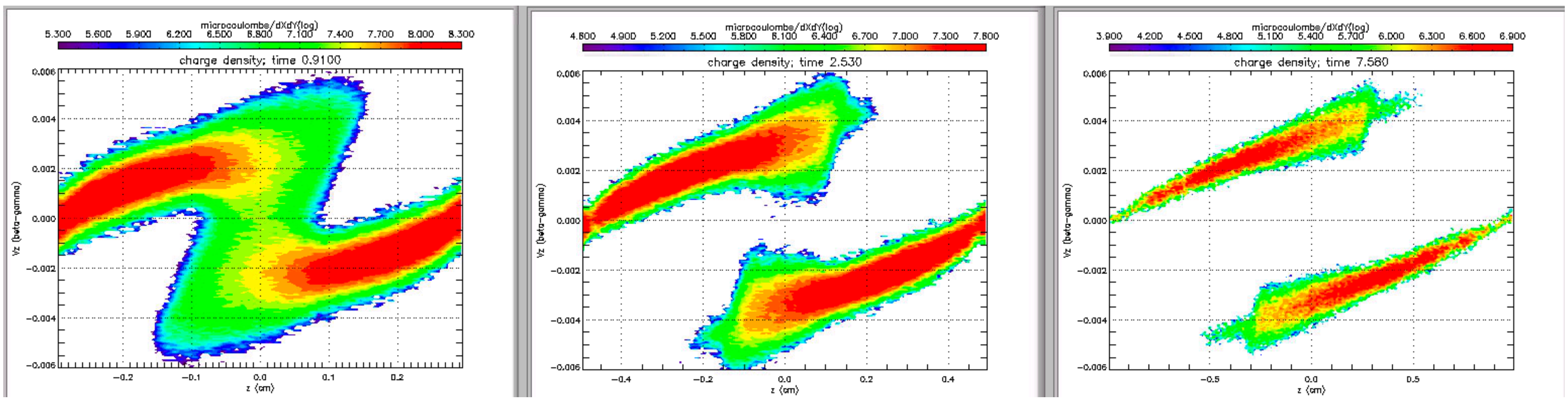
Clear dependence of neutron energy on angle was observed in the simulations for the CD →← CH case.
Was this present in experimental neutron data?

Future NIF experiments will probe into less collisional regimes

Planned experiments will reach the collisionless regime

Deuteron phase space for CD <→ CD case for 3 separation distances

6 mm | 10 mm | 20 mm



As the separation distance increases, we will approach a completely collisionless regime, and also keep the density high enough so that there will enough c/ω_{pi} 's to see collisionless shock formation.